

AEROSE 2004 Cruise Results and Ocean Emissivity

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AIRS Science Team Meeting
31 March 2004

AEROSE 2004 Overview

- The **Aerosol and Ocean Science Expedition (AEROSE)** was conducted onboard the **NOAA Ship Ronald H. Brown (RHB)** in the tropical North Atlantic Ocean from 29 February to 26 March 2004 in collaboration with the NOAA Center for Atmospheric Sciences (NCAS) at Howard University.
- The NOAA RHB set out from Bridgetown, Barbados traveling eastward toward Africa. Near the African coast, the ship turned north toward the Grand Canaries. After a port-of-call in Las Palmas, Gran Canaria, the ship then returned to San Juan, Puerto Rico on 26 March.
- Atmospheric and oceanographic measurements were acquired with a complement of in situ and remote sensing sensors under dust and non-dust conditions.
- The eastward trans-Atlantic leg of the cruise included oceanographic stations for subsurface CTD sampling and XBT profiling.
- The cruise included educational component (student participation, courses taught underway, ship tours while in ports).
- A follow-on Saharan dust cruise is in the RHB draft allocation plan for Summer 2005.

AEROSE Data of Interest

- Marine Atmospheric Emitted Radiance Interferometer (M-AERI)
 - Ship-based FTS designed to sample atmospheric and surface IR emissions
 - Algorithms derive skin SST (<0.1 K), emissivity and BL profiles
- Calibrated InfraRed In situ Measurement System (CIRIMS)
 - Reduced complexity & cost; autonomous
 - Designed solely for providing accurate radiometric SST ground truth
- Vaisala RS80/90 RAOBs
 - \sim 3-Hourly throughout cruise, including AIRS overpasses
- Microtops handheld sunphotometer
 - Surface based measurements of aerosol optical depth (AOD)
- Standard oceanographic/meteorological surface data from ship

M-AERI and CIRIMS

Legacy: 1996 Combined Sensor Program (CSP)

NOAA Ship Discoverer
Pago Pago, March 96



UW-Madison M-AERI Prototype
Onboard NOAAS Discoverer

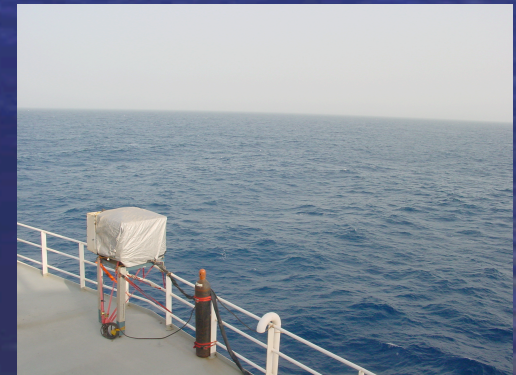


Today: 2004 Aerosol and Ocean Science Expedition (AEROSE)

U. Miami M-AERI & UW/
APL CIRIMS



NOAA Ship Ronald H. Brown
Bridgetown, Feb 04

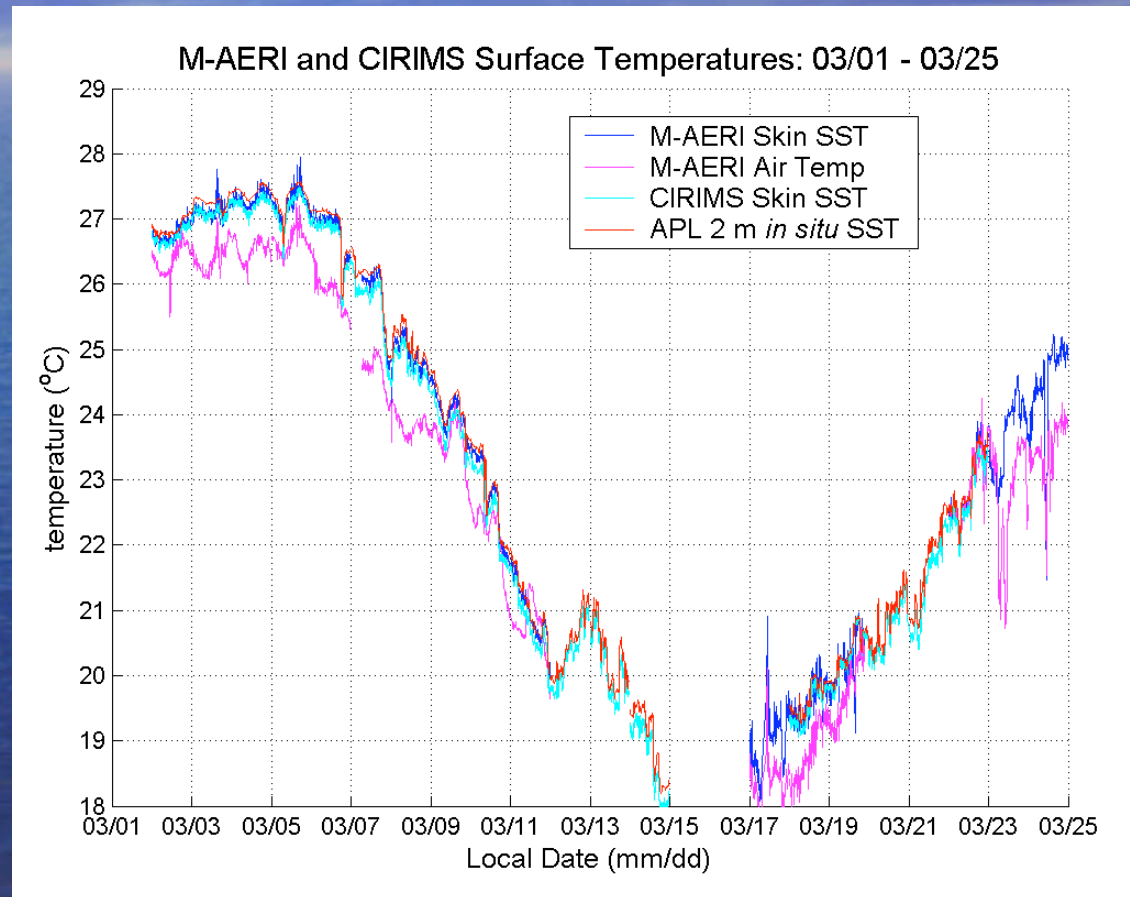


SST Ground Truth for Cal/Val

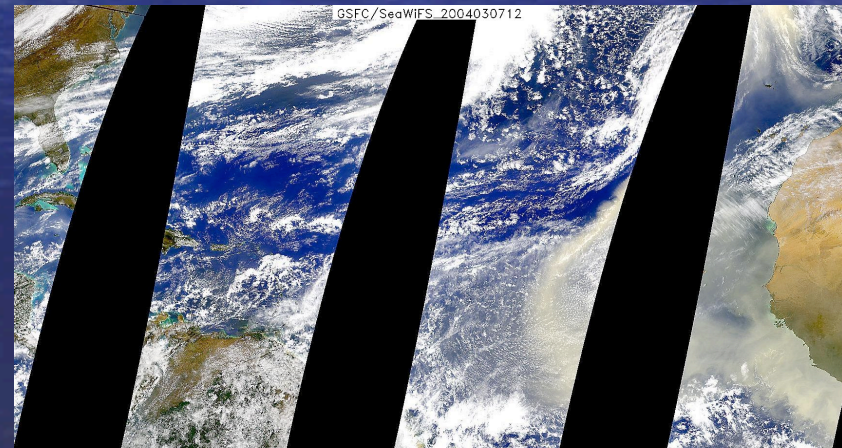
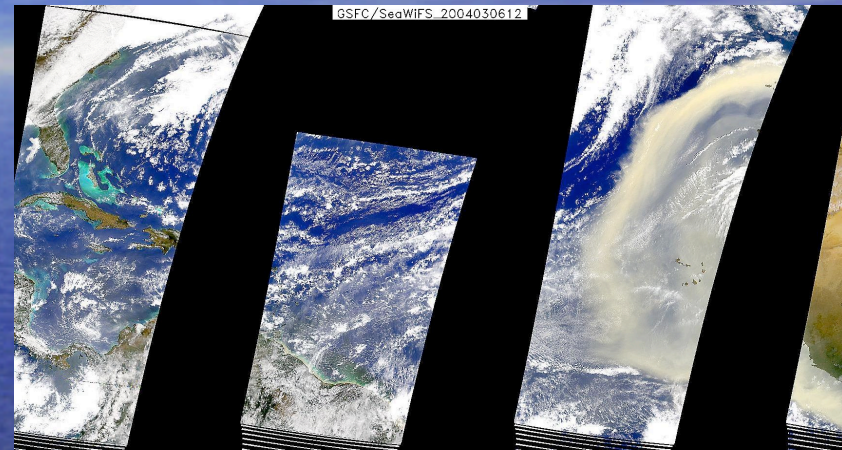
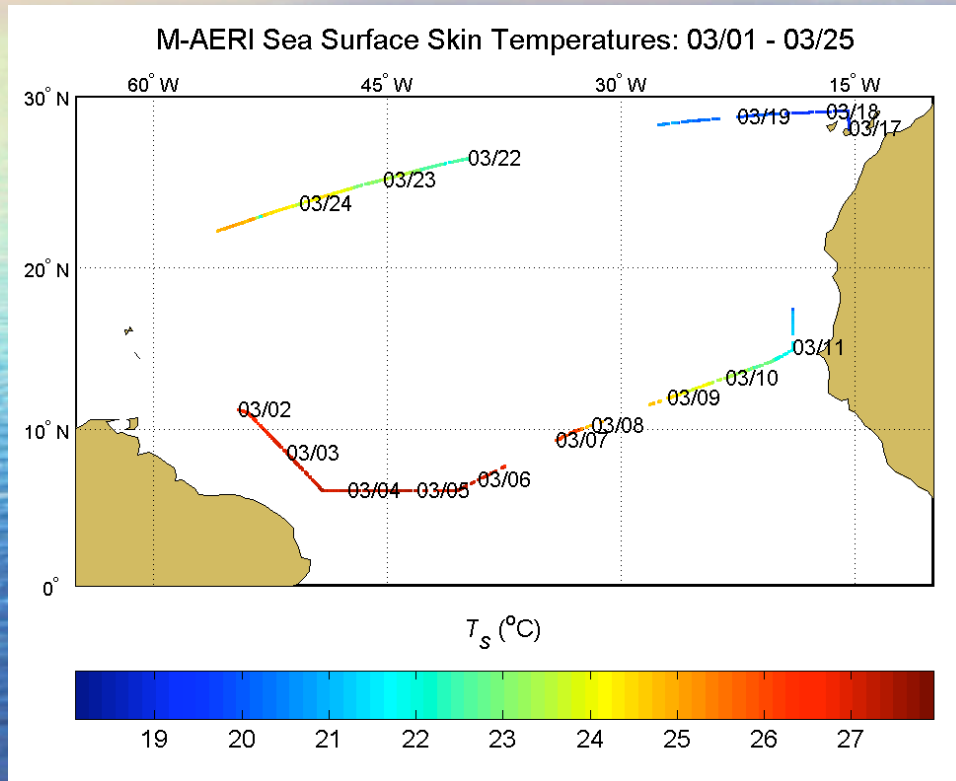
- IR and MW detectors remotely sense radiometric “skin” temperature
- Skin SST differs from “bulk” SST measured in situ (e.g., buoys $\sim -0.1 \pm 1$ K)
- This uncertainty imposes significant limits upon satellite cal/val efforts – radiometric ground truth is thus essential
- M-AERI and CIRIMS are examples of shipboard instruments designed to obtain accurate radiometric SST

AEROSE M-AERI vs. CIRIMS

- M-AERI and CIRIMS are two distinctly different IR instruments with completely different algorithms
- During AEROSE, significant surface winds yielded a skin SST systematically cooler than the 2 m in situ measurement



Dust Event



Dust Event

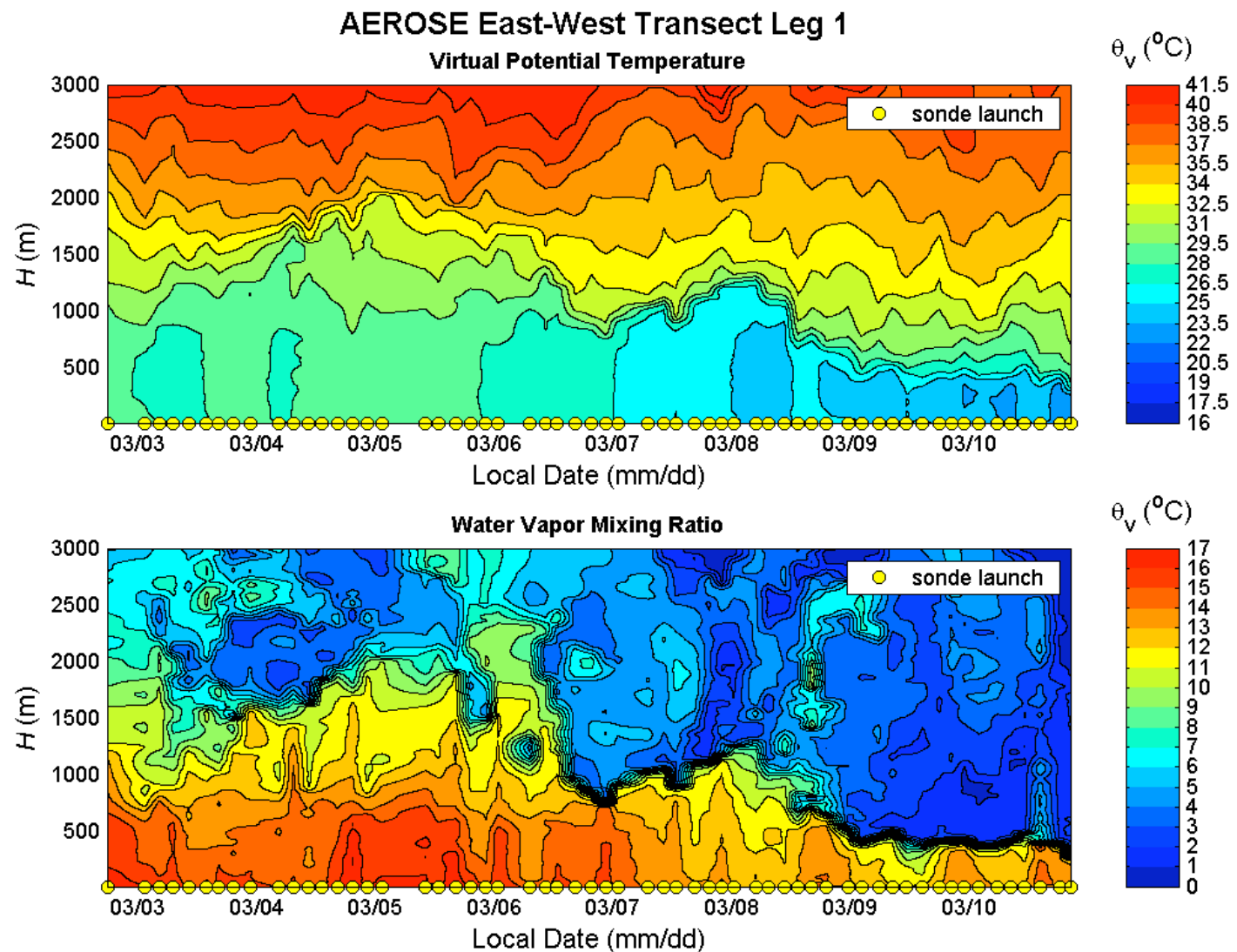
17:00 UTC, 6 March 04



11:00 UTC, 7 March 04



AEROSE 3-Hourly RAOBs



The background of the slide is a photograph of a vast, deep blue ocean under a bright blue sky with wispy white clouds. A bright, colorful rainbow-like lens flare is visible on the left side, extending from the horizon towards the top left corner. The text "Ocean Emissivity/Reflectivity" is centered in the middle of the image in a white, sans-serif font.

Ocean Emissivity/Reflectivity

Radiative Transfer Equation (RTE)

Cloud free, non-scattering, azimuthal symmetry

$$R_v(\theta_0) = \left[\epsilon_v(\theta_0) B_v(T_s) + \int_0^{\pi/2} r_v(\theta, \theta_0) I_v^\downarrow(\theta) \cos\theta \sin\theta d\theta \right] \tau_{vs}(\theta_0) + I_v^\uparrow(\theta_0),$$

$R_{vs}(\theta_0)$
 Surface Leaving Radiance

$R_v(\theta_0) \equiv$ observation

$R_{vs}(\theta_0) \equiv$ surface reflected radiance

$\epsilon_v(\theta_0) \equiv$ surface emissivity

$\tau_{vs}(\theta_0) \equiv$ path transmittance

$r_v(\theta, \theta_0) \equiv$ bidirectional reflectance

$I_v^\downarrow(\theta) \equiv$ downwelling radiance

$I_v^\uparrow(\theta_0) \equiv$ upwelling radiance

$B_v(T_s) \equiv$ blackbody surface emission

$\theta \equiv$ local zenith angle

$\theta_0 \equiv$ local satellite zenith angle

Ocean Surface IR Emissivity and Reflectance

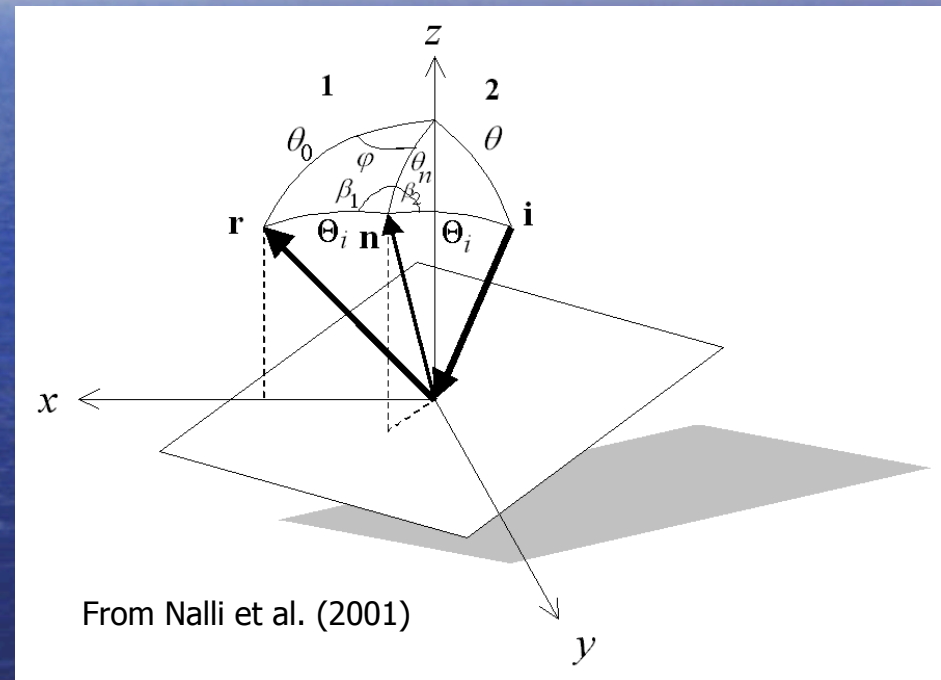
- Radiance emissivity models (e.g., Wu and Smith, 1997; Watts et al., 1996; Masuda et al., 1988) have been derived from Cox-Munk wave slope statistics.
- Lookup tables (LUT) of model emissivity can be used in radiative transfer modeling.

$$\epsilon_v = f(v, \theta_0, \bar{V}), \quad \bar{V} \equiv \text{mean surface wind speed}$$

- Quasi-specular reflectance of atmospheric radiance is a more challenging problem:
 - Surface is neither specular nor Lambertian, but **quasi-specular**
 - Thus, depends upon the hemispherical radiance distribution
 - Using $1 - \epsilon$ leads to systematic underestimation of radiance in microwindow channels
 - This systematic error is significant for SST applications requiring high accuracy

Quasi-Specular Reflection Model

- **Kirchhoff Approximation:** Surface waves have dimensions large compared to IR λ (geometrical optics limit)
- **Fresnel Reflectivity:** Known from observed refractive indices
- **Facet Model:** Cox-Munk mean square slope statistics dependent upon local surface wind speed
- Transform slope coordinates to local zenith and azimuth angle
- Account for **wave blocking** and **reflected emission** consistent with the emissivity model



Cartesian coordinate system for a wave facet under the Kirchhoff approximation

Reflected Radiance

The reflected IR radiance from the atmosphere is then given by

$$R_{vs}(\theta_0) = \int_0^1 \int_0^{\varphi_2} \rho_v(\varphi, \mu_n) I_v^\downarrow[\theta(\varphi, \mu_n, \mu_0)] P(\varphi, \mu_n, \mu_0) d\varphi d\mu_n,$$

θ, φ are the zenith and azimuth angles

φ_2 is the azimuth upper limit that eliminates self-blocking

$$\mu_0 = \cos\theta_0, \quad \mu_n = \cos\theta_n$$

θ_n is the facet normal zenith angle

ρ_v is the Fresnel reflection coefficient

P is a normalized Cox - Munk wave slope PDF

This equation essentially describes the reflected radiance as the ensemble effect of rays reflected from all possible slopes into the field of view of the observer.

Reflection Diffusivity-Angle

For convenience in retrievals, computation is greatly reduced by introducing a **reflection diffusivity-angle** $\bar{\theta}_v$ (Nalli et al., 2001)

$$I_v^\downarrow(\bar{\theta}_v) \equiv \frac{\int_0^1 \int_0^{\varphi_2} \rho_v I_v^\downarrow(\theta) P d\varphi d\mu_n}{\int_0^1 \int_0^{\varphi_2} \rho_v P d\varphi d\mu_n},$$

which leads to

$$R_{vs}(\theta_0) = I_v^\downarrow(\bar{\theta}_v) \bar{r}_v(\theta_0, \bar{V}),$$

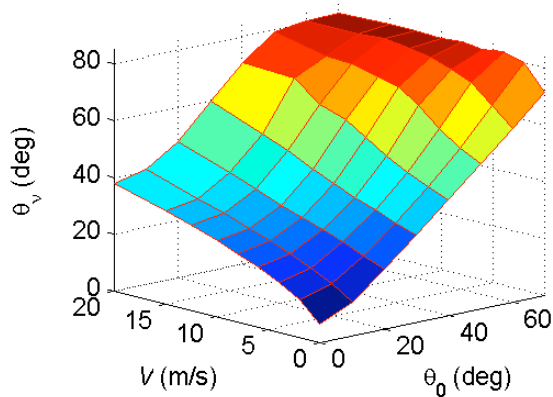
from which $\bar{\theta}_v$ can be determined by finding the zeros of the equation.

A fast transmittance model can be used to calculate LUT for a range of wavenumbers, wind speeds and atmospheric opacities, i.e.,

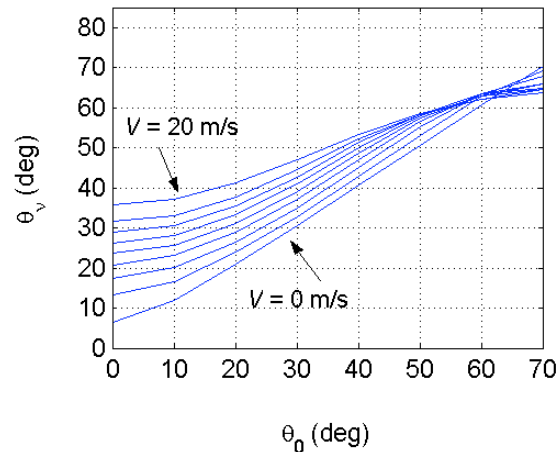
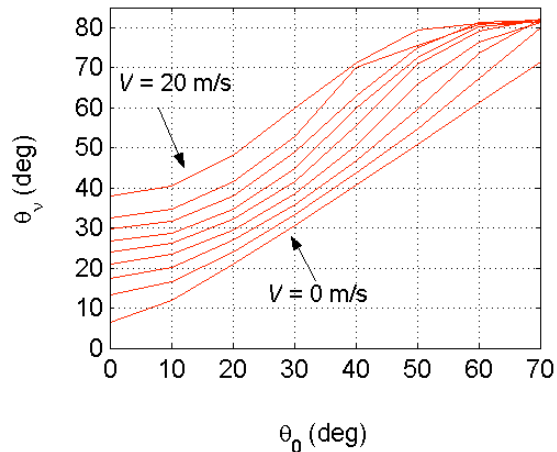
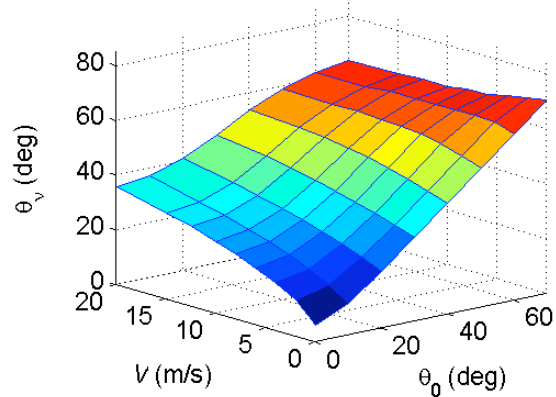
$$\bar{\theta}_v = f(\nu, \theta_0, \bar{V}, \tau_{v0}(\theta_0))$$

Behavior of $\bar{\theta}_v$

Dry Atmosphere, $\nu = 876.5 \text{ cm}^{-1}$



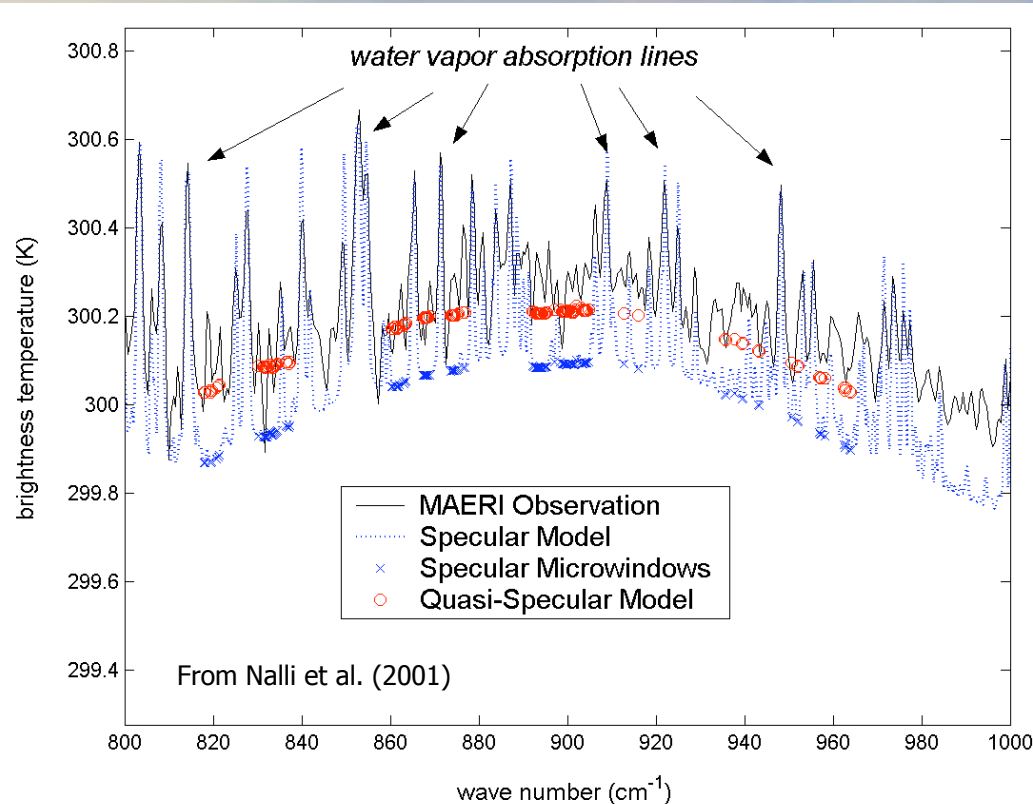
Moist Atmosphere, $\nu = 876.5 \text{ cm}^{-1}$



- $\bar{\theta}_v > \theta_0$ implies an enhancement of reflected intensity
- Reflection becomes specular with decreasing winds
- For dry atmosphere, always $\bar{\theta}_v < \theta_0$
- Similarly for moist atmosphere (right plots), except at $\theta_0 = 70^\circ$, where $\bar{\theta}_v > \theta_0$

for non-zero winds

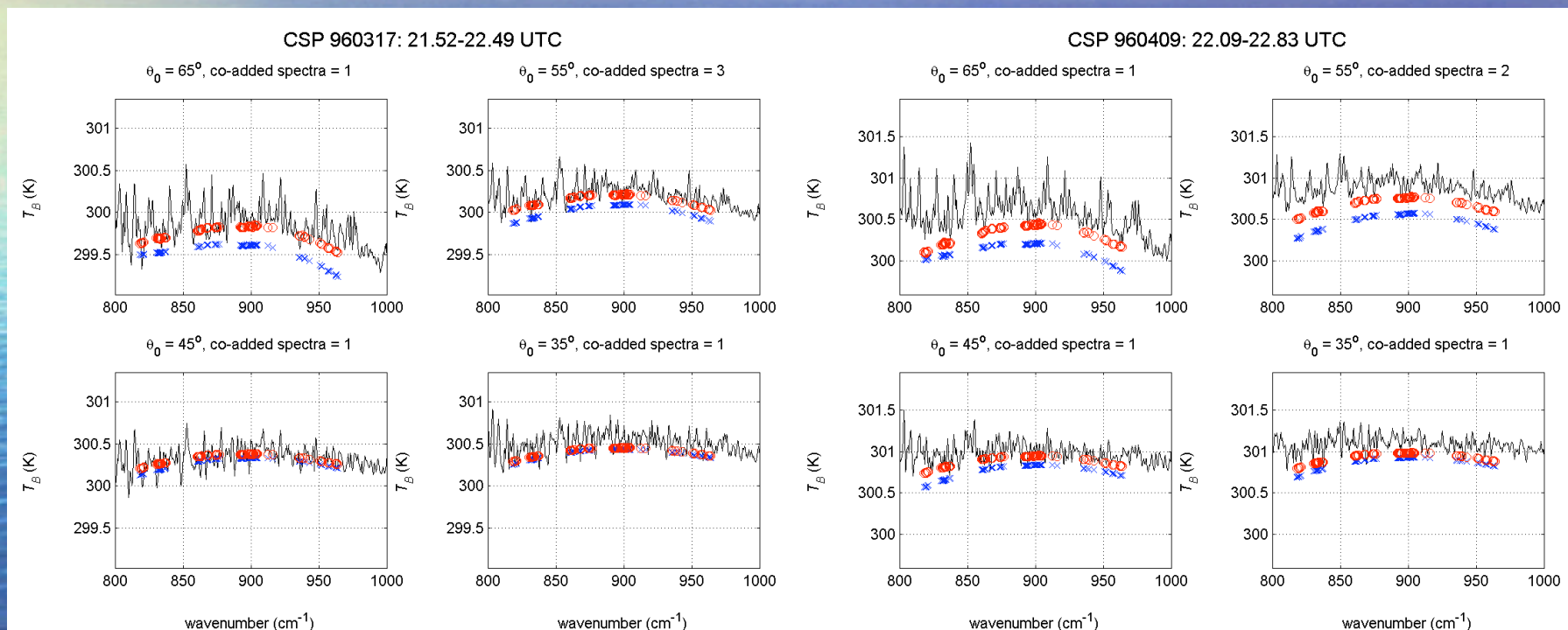
M-AERI Ocean Surface Spectra



- Non-unity emissivity signal is apparent
- Water vapor absorption lines appear as “spikes”
- The specular model underestimates the observation in microwindows by ~ 0.2 K

Model calculations versus M-AERI observation for 55⁰ view angle at 22:18 UTC, 17-Mar-96.

Model versus M-AERI



17-Mar-96, 22:18 UTC (2.1 S, 179.9 W)

$V = 4.9 \text{ m/s}$; roll = -1.08°

09-Apr-96, 22:28 UTC (7.3 N, 172.6W)

$V = 13.7 \text{ m/s}$; roll = -0.45°

Findings from CSP

- Specular reflection underestimates the observed brightness temperature by as much as 0.4 K at larger zenith angles.
- Reflection-diffusivity model improves agreement by a factor of ~ 2
- The remaining deficit was partially due to the lower boundary of the uplooking model truncated at 1000 hPa
- More validation against M-AERI is desirable: AEROSE...

